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Advances on air conditioning and heat pump system in electric vehicles – A review

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ABSTRACT

There is a rising interest in electric vehicle's climate control system including cooling and heating. Electric vehicles (EVs, including hybrid electric vehicles and full electric vehicles) have inadequate waste heat to warm up the cabin and the climate control system has a very significant effect on the energy consumption efficiency and operating mileage. Heat pump (HP) is one approach for energy consumption efficiency improvement in EVs which can supply cooling and heating capacity. A literature review was performed on the vapor compression HP cycle design, performance characteristics, and challenges for variable working fluids for electric vehicles. The non-vapor compressor HP systems were also analyzed including the applications of magnetocaloric effect and thermoelectric effect. It seems heat pump system is a reasonable and feasible option in EV's climate control system if some essential issues could be solved. The mobile climate control systems based on magnetocaloric effect and thermoelectric effect could be the supplementary methods in future applications.

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1. Introduction

Mobile climate control system includes air conditioning (AC, cooling) and heating, which is an essential subsystem in vehicles. It functions in two layers. One is operating safety in visibility

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(defogging and deicing), and the other is to maintain the cabin comfort including temperature, relative humidity and air velocity.

Considering the global warming and CO_2 emission, more efficient engines with less waste heat is being developed. At the same time, electric vehicles (EVs) are becoming increasingly popular. This trend is raising new challenges in mobile climate control system design. For example, in winter, the waste heat from gasoline engine will be used for cabin heating and window de-icing, whose amount is more than 5 kW. But in full hybrid electric vehicles, engine waste heat is insufficient (waste heat from an electric engine is about 2 kW at 40 °C) and more electric energy from the battery is needed, which will affect the driving mileage significantly. Hannan et al. [1] reviewed the challenges in hybrid electric vehicles (HEVs), but they did not mention the effect of climate control system on batteries' performance. Khoury and Clodic [2] experimentally studied the effect of electrical AC operation on the electricity consumption in a hybrid electric vehicle. In their study, the most important achievement was that some test procedures and testing conditions were proposed according to the driving conditions, climatic conditions and AC operation conditions based on the others studies [3]. The test results showed that AC system became the largest energy consumption system for a highly efficient hybrid vehicle and AC system had a high impact on vehicle overall fuel consumption. In full electric vehicles (FEVs), the newest heat pump (HP) technologies could reduce the driving distance with fully charged batteries by 8% in cold conditions [4,5]. The experimental data showed that AC full load driving characteristics of different road and speed cycles had a significant influence on the total driving range [6]. The reduction percentage was up to 16.7% and 50.0% for cooling and heating, respectively. It was concluded that the driving range reduction was very sensitive on cooling and heating system operations. The difficulty is improving the efficiency of climate control system and minimizing energy consumption in both cooling and heating modes.

In the present paper, the state-of-art technologies in air conditioning and heat pump systems available for electric vehicles will be comprehensively reviewed. The electric vehicles (EVs) include hybrid electric vehicles (HEVs, including full hybrid, mild hybrid, plug-in hybrid) and full electric vehicles (FEVs). The structure of the present review paper is organized as follows: First, the AC/HP systems based on vapor compression cycle are analyzed for EVs' applications. In this section, the technology, developments and challenges for different working fluids and system types are comprehensively reviewed. Second, the AC/HP systems based on non-vapor compression cycles including the applications of magnetocaloric effect and thermoelectric effect are mainly introduced from materials, system structures and performance. Finally, the conclusion is drawn according to the previous reviews and analysis.

2. AC/HP based on vapor compression cycle

The vapor compression cycle is still dominant in mobile air conditioning systems. Considering convenient replacement, low cost and easy maintenance, the mobile industry desires a direct transit from conventional vehicles to electric vehicles. From this point of view, there are some proposals based on the current mobile AC and heating technologies.

2.1. Advances in R134a systems

In general, air conditioning system plus electric resistance heater/fuel fired heater is the basic option for EVs. The option seems the easiest one with few changes. The changes are electrically driven compressor instead of mechanically driven compressor and electric heater instead of hot coolant heater core. A 42 V electric air conditioning system called E-A/CS was proposed, which consisted of a compressor, a blower, an integrated positive thermal coefficient (PTC) heater, inverter, pipes and other heat exchangers [7]. The biggest advantage of a 42 V AC system was reducing the system electric amperage below 100 A and increasing the component overall efficiency roughly to as high as 50–80%. The cabin temperature curve showed the E-A/CS could keep a more stable and comfortable interior environment compared with an externally controlled mechanical compressor system under hot weather conditions. The system could still achieve a relatively better thermal environment under very cold weather conditions, but its energy was derived from the battery electricity. The system also possessed advantages in environment protection, system configuration and safety. Currently, PTC heater is widely used as auxiliary heating in gasoline engine vehicles and EVs. There are some barriers for PTC heaters, such as high cost with high power (>2 kW) and more energy consumption (the ratio of heat output to electric input is less than 1.0). The PTC heater can lead up to 24% losses of the driving distance with fully charged batteries [5]. According to the second law of thermodynamics, the coefficient of performance (COP) of a heat pump system is larger than 1.0. From this point of view, a heat pump system appears a reasonable method to improve the efficiency of climate control system in EVs.

Suzuki and Katsuya [8] compared the air conditioning system between the conventional vehicle and electric vehicle and pointed out the necessary modifications for system efficiency improvement. They also proposed a heat pump system for electric vehicle, in which one 4-way valve, two expansion valves and several check valves were used to reverse the refrigerant flow direction as shown in Fig. 1. This system could provide cooling, heating, demisting and dehumidifying. The system details were published in the technical paper [8] including system diagram, electric compressor and electric expansion valve specifications. The working fluid was R134a and only two test data were published. The experimental results showed the system cooling and heating capacities under 40 °C and -10 °C ambient temperature were 2.9 kW and 2.3 kW, respectively, and the COPs were 2.9 and 2.3, respectively. This technical paper seems the first R134a heat pump system for EVs with open experimental data.

Promme [9] described a similar heat pump system for electric vehicle as Suzuki and Katsuya [8]. But he pointed out that there was an ice formation on the heat exchanger surface when the ambient temperature was below -10 °C. He proposed an improved heat pump system with an additional external heat source which could utilize the waste heat of the main battery, driven electric motor and its power control unit as shown in Fig. 2. This was an optimized and simplified system with the same cooling/heating functions. One specially designed device, called bi-directional receiver/expansion device, as shown in Fig. 3 could be used to realize the following functions: refrigerant filtering and drying, refrigerant accumulator, refrigerant expansion and cooling/heating mode operation. The bi-directional receiver/expansion device optimized the system and six components were replaced (2 expansion valves, 2 check valves, and 2 receivers). The bench test results of the improved system showed that 2.5 kW heating capacity was gained from the heat pump system under -10 °C ambient temperature, in which 0.5 kW heat was recovered from the battery. In this condition, the energy saving on the main battery was estimated to be about 15% compared with a PTC heater system. The improved one was less sensitive with frost formation on the external heat exchanger and more stable in winter conditions compared with the conventional heat pump system. In the AC mode, cabin temperature of 24 °C could be

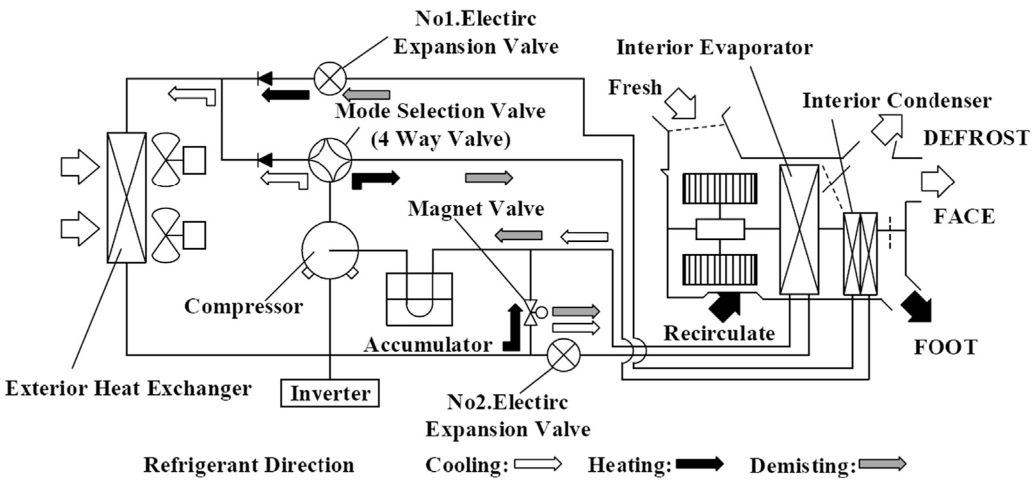

Fig. 1. R134a heat pump system structure and operation for electric vehicles [8].

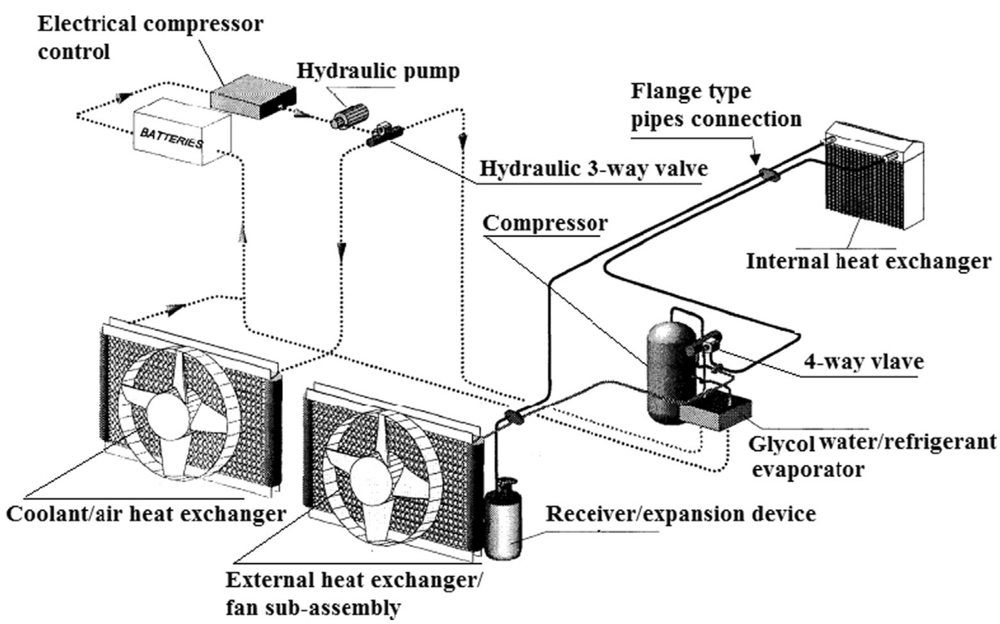

Fig. 2. Complete improved heat pump system [9].

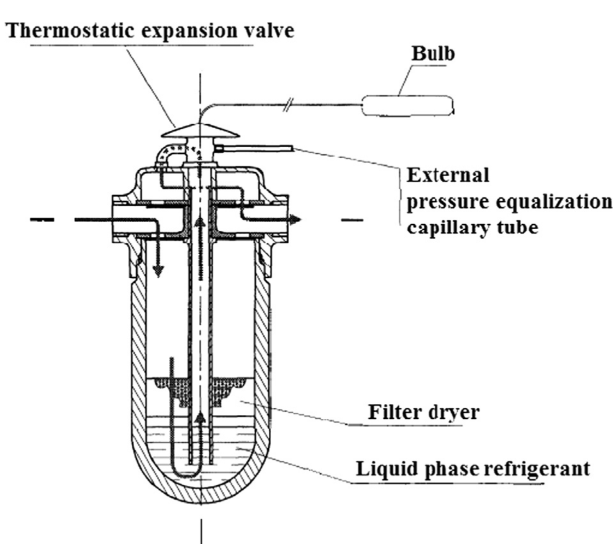

Fig. 3. Bi-directional receiver/expansion device [9].

obtained with a similar or less cool-down time than that of the conventional AC system.

After the analysis of the advantages and disadvantages of engine/battery-dependent or -independent technologies as shown in Table 1, Bilodeau [10] proposed the integrated climate control system. The design conditions including the comfort requirements in various ambient conditions, system load, thermal resistance, battery or other electronics should be considered simultaneously. Based on this concept, a new climate control system called Regenerative High Performance Heat Pump (RHP2) was established. In the RHP2 system, waste heat during the exothermic battery operation and thermal energy recovered from evacuated stale air were taken into account. The system had a relative high COP of 2.9 even under severe driving conditions in the laboratory. The real performance in a post service delivery truck implied it could operate independent of weather conditions as low as $-25\,^{\circ}$C without loss of COP, which was a real improvement compared to the normal heat pump system. However, in that research the system and components specifications and cooling performance were not released.

Table 1
Comparison of engine/battery-dependent and -independent technologies [10].

Electrical elements (resistance)	Cause serious range problems (decreasing the driving range with full charge) Do not allow for management of accumulator heat
Diesel or gasoline fired systems	Should not be considered as a real Zero Emission Vehicle subsystem Do not allow for air conditioning or thermal management
Air/air heat pumps	Cause range problems at low temperature (decreasing the driving range with full charge) (< -5 °C) Do not provide weather protection for accumulators

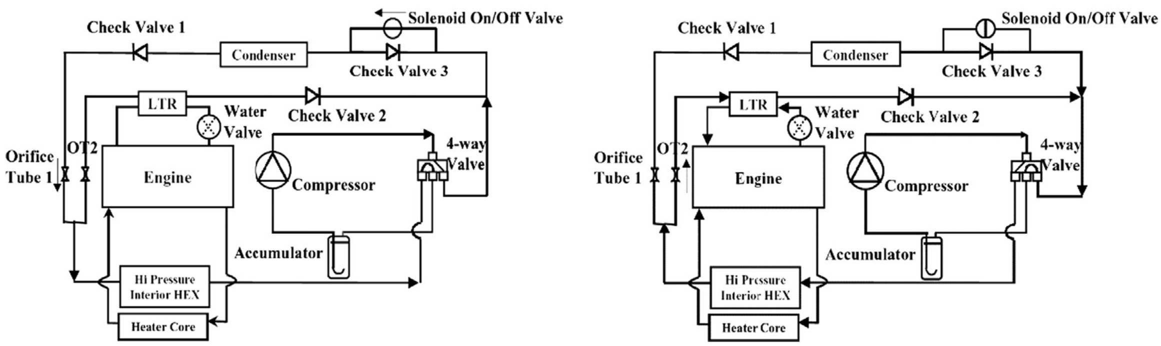

Fig. 4. Schematic of R134a heat pump system (left: cooling mode; right: heating mode) [12].

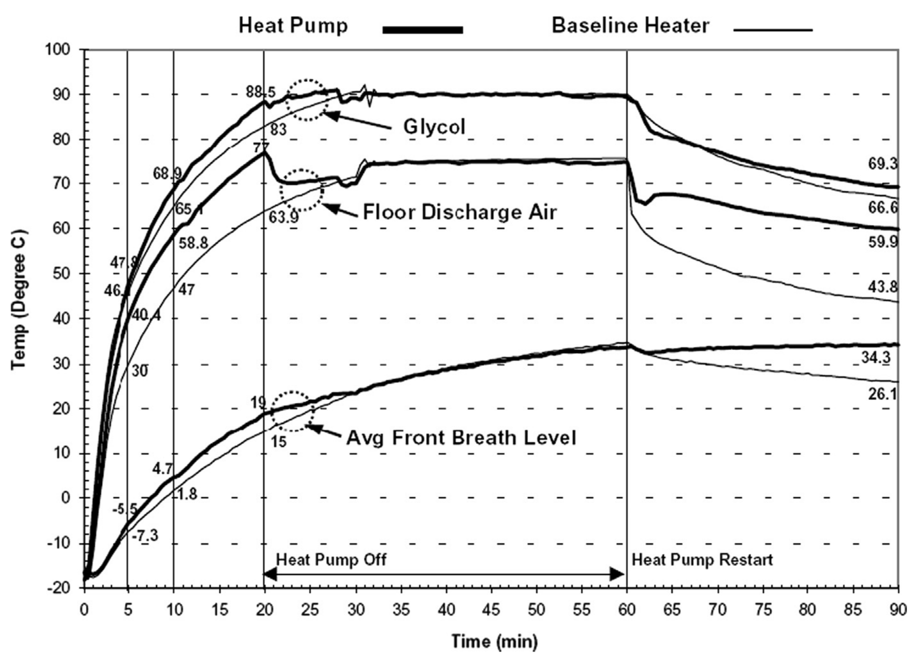

Fig. 5. Warm-up performance between baseline and heat pump [12].

Scherer et al. [11] developed R134a and R152a heat pump systems with the 3-way valve to control the refrigerant flow during the cooling and heating mode switches. But only the heating performance data was released. During the heating mode, the engine coolant was used as the heat source, which had a better quality and eliminated the ice accumulation issue on the exterior heat exchanger surface. The steady performance showed the system could supply more than 9.0 kW heat capacity under ambient temperature -10 °C condition. In the warm-up testing, the R134a and R152a heat pump system could shorten the warm-up time to the comfortable cabin temperature compared with the original heater core heating system. But these heat pump systems were not suitable for FEVs because there is no such engine coolant heat resource for the exterior heat exchanger.

Meyer et al. [12] developed a new heat exchanger (liquid-to-refrigerant, LTR) and a high burst-pressure heat exchanger to replace the heat pump evaporator and condenser under cold conditions, respectively. In their system as shown in Fig. 4, the glycol heat source was used to avoid the deterioration of R134a heat pump performance in winter. Because the system charges under hot and cold conditions were different, two check valves were used to avoid system unsteadiness by blocking the refrigerant flowing into the system. A 4-way refrigerant valve was used to control the flow direction during the AC and heating mode switches. There were several solenoid valves to control the flow direction or protect the system. For the throttling device, two different orifice tubes were selected for different modes. The wind tunnel warm-up performance tests under different vehicle speed conditions showed that the heat pump system increased the interior temperature quicker than that of a conventional heater core system as shown in Fig. 5. And at the same operation time, the interior temperature of the heat pump system is higher than

that of the heater core system. The authors also proposed some additional heat pump systems to solve some engineering challenges such as flash fogging during the AC/HP mode transit. But these systems would add more heat exchangers and valves. The system packaging and cost would be an issue in the application. Meanwhile, it would be not suitable for a FEV because there is no glycol heat resource.

Antonijevic and Heckt [13] experimentally studied a supplemental heat pump system for mobile heating system. The prototype system could gain additional 1.5 ~ 3.0 kW heat capacity under different ambient temperatures and driving conditions. The authors also concluded the supplementary system speeded up the warm-up period no matter how cold the engine was. Using the system, the vehicle fuel consumption also was improved compared to those of the heater core systems and PTC heater supplementary systems. Jokar et al. [14] set up a dual-loop system that could be run under winter and summer conditions. It was composed of a, 4-way valve, exterior and interior heat exchangers. The difference with the other R134a heat pump systems was the vehicle cabin cooled by an internal cooler. The fluid absorbing heat in the internal cooler is not a traditional refrigerant but a coolant. The test results showed the system could run very well in AC mode in various environmental and cabin conditions. Unfortunately, no heat pump test result was published. The system was simple and ran smoothly but more heat exchangers and more glycol-coolant would increase the system cost and weight. However, the coolant had a higher thermal storage capacity and it was better for idle condition but worse for warm-up and cool-down conditions.

Shin et al. [15] tried a new heat pump system in bus climate control system. In this system, the engine coolant was used as a heat source. Mainly, the bench and the on-vehicle experimental results of the new heat pump system were compared with the heating performance of the conventional heater core system with an auxiliary heater. Considering the bus size, cost, complexity, performance and efficiency of the whole system, two 3-way valves were used to replace the conventional 4-way valve to reverse the refrigerant flow when the AC/HP mode switched. The bench tests showed that the HP heating capacity was strongly dependent on the compressor speed and the coolant temperature, which was the heat source. The on-vehicle tests showed that the vehicle warm-up temperature was lower during the first 17 minutes and then larger after 17 minutes than that of a conventional heater core system. It was concluded the HP system should face the bigger challenges when the vehicle speed was idle. The authors also implied that the new HP system needs more improvements and more studies on operation cost, compartment comfort and new alternative refrigerants.

Some researchers numerically studied the mobile thermal management system. Yokoyama et al. [16] developed a simulation system called Thermal Link System to analyze the EV thermal management system. The system was a heat pump system with a 4-way valve to control the refrigerant flow direction. The cooling and heating capacity were transferred by a secondary loop to the compartment and devices. Under the cooling mode, the refrigerant was divided into two directions to heat exchangers of cabin and devices (could be called a dual-evaporator system), which was different from the previous HP systems. The heating mode could reduce the electrical consumption to 600 W and gain 2000 W heating capacity. It meant the COP was more than 3.3.

Kowsky et al. [17] reconsidered the concept of secondary loop and designed a Unitary Heat Pump Air Conditioner (HPAC) system with an additional coolant heat exchanger. Using this compact system, both heating and cooling could be supplied without reversible refrigerant flow direction but with coolant flow switches as shown in Figs. 6 and 7. The system included an electric compressor so it could be used in HEVs/FEVs. Since the system operation cycle was always the same even though heating or cooling switched, the flash fogging issue existing in the refrigerant heat pump system would be eliminated. The Unitary HPAC had the ability to dehumidify and heat at any time. The Unitary HPAC could improve HEV driving range. According to different cooling and heating control strategies, the system combined with Unitary HPAC and PTC heater would reduce electric energy consumption. PTC heater would be open as auxiliary heating supply only when the ambient temperature was lower than a specific value. The analysis results shown in Fig. 8 implied that the energy savings and fuel consumption had been improved obviously.

2.2. Advances in CO_2 systems

CO_2 is an old but natural refrigerant with lower global warming potential (GWP, GWP = 1) and no ozone depletion potential (ODP, ODP = 0). Because of its low critical temperature (31.1 °C), it mostly is operated in transcritical cycle [18]. In CO_2 transcritical cycle, the CO_2 vapor is cooled in vapor phase and the condenser is called the gas cooler [18,19]. Since the middle of the 1990s, CO_2 air conditioning and heat pump technologies have been developed rapidly and widely. CO_2 can be used in residential, commercial and mobile devices. Kim et al. [20] carried out a comprehensive

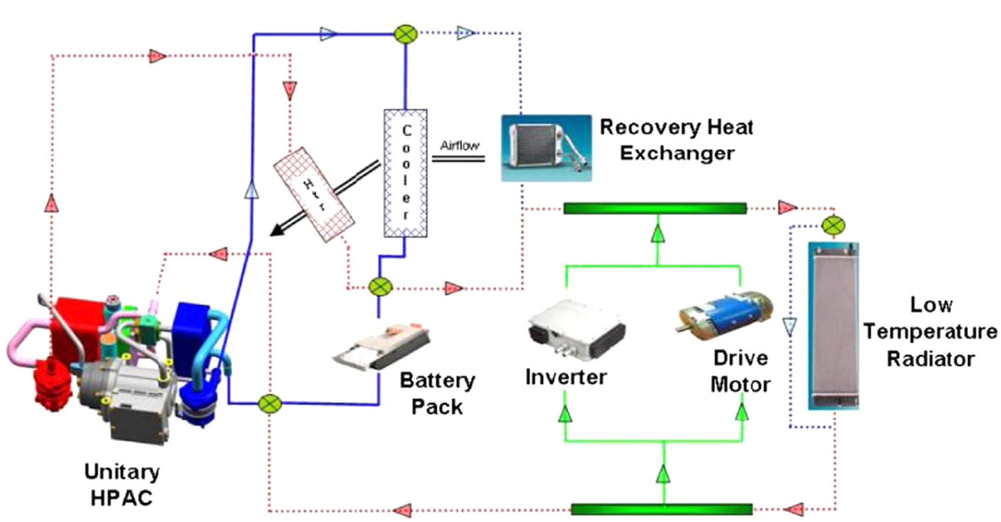

Fig. 6. Cooling model in Heat Pump Air Conditioning (HPAC) system [17].

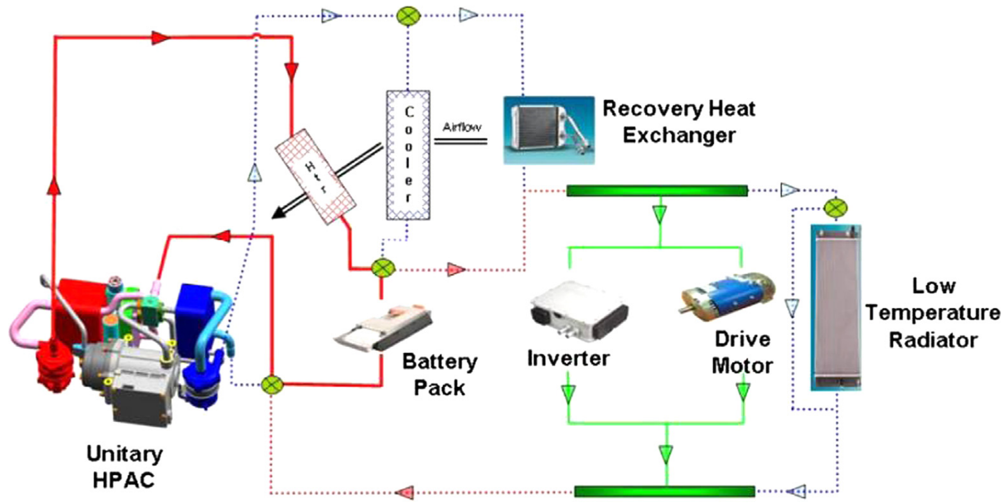

Fig. 7. Heating model in Heat Pump Air Conditioning (HPAC) system [17].

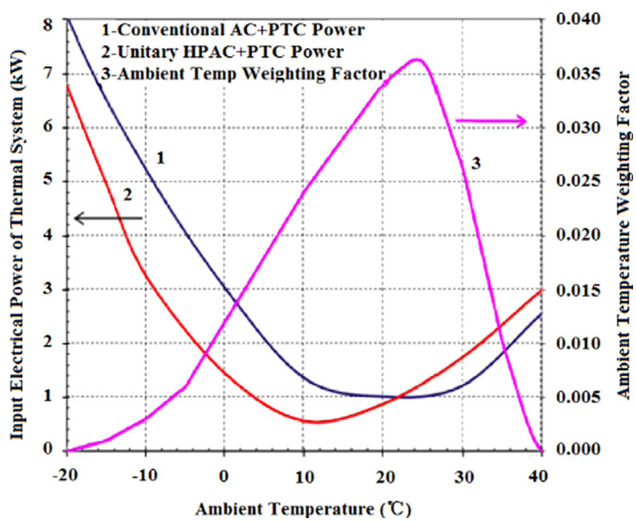

Fig. 8. Input power with different ambient temperatures [17].

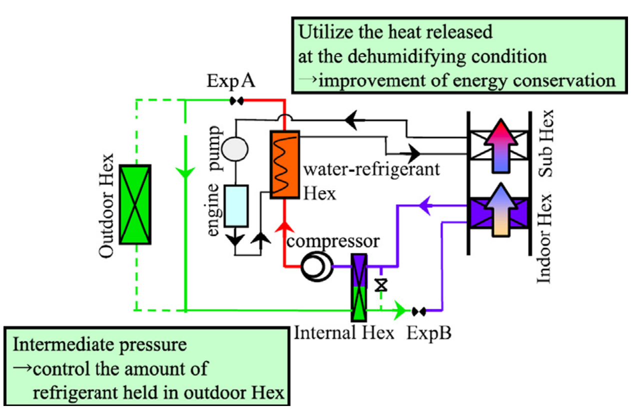

Fig. 9. CO_2 cooling and heating/dehumidifying system [25].

technology review on CO_2 vapor compression cycle including properties, cycles, components and applications. The performance of CO_2 vapor compression systems for gasoline engine vehicles will not be reviewed again as Kim et al. [20]. In the present paper, CO_2 mobile air conditioning and heat pump system available for EVs will be discussed. CO_2 systems have special benefits in heat pump mode such as high heating capacity and COP even at low ambient temperature and high air outlet temperature off gas cooler to vehicle cabin.

The earlier CO_2 prototype mobile heat pump systems came from the works carried out by Air Conditioning and Refrigeration Center (ACRC) at University of Illinois at Champaign-Urbana [21–23] and Hafner [24]. During these researches, some distinct features were revealed: higher heating capacity, higher COP, and smaller compressor volume although the heat exchanger was not perfect. The transient warm-up test showed that it could supply the highest heating capacity at the engine start when it was needed the most. Kim et al. [20] analyzed in detail the advantages and disadvantages of CO_2 mobile HP system. The CO_2 mobile HP system has the same problems on defrosting of exterior heat exchanger and performance deterioration under cold ambient temperature conditions as well as R134a HP system. They pointed out that there are a number of substantial issues that cannot be addressed such as the outdoor heat exchanger will accumulate frost, and perhaps ice as water is splashed on it from the road. The defrosting method used in residential HP system is not suitable for mobile HP systems because of a more compact cabin and quick temperature decrease.

Tamura et al. [25] developed a prototype CO_2 mobile cooling and heating system for medium-sized cars. The system performance was superior to that of an R134a system. Meanwhile, the heating COP ratio of the CO_2 system to R134a system was 1.31 when a coolant flow was used as the heat source. The special design in Tamura et al.'s work was an intermediate pressure control method for adjusting the optimum refrigerant amount as shown in Fig. 9. The intermediate pressure was maintained in the outdoor heat exchanger to avoid the unbalance in the optimum amounts of refrigerant for cooling and heating.

A model of CO_2 heat pump and hot gas cycle were developed and compared with the test data [26]. The numerical model agreed well with the test data in both heat pump and hot gas cycle. The result showed that CO_2 heat pump could supply adequate heating capacity under ambient temperature of $-5\,^{\circ}C$ but with high interior air volumetric flow rate, the outlet temperature from the heat exchanger was lower than $20\,^{\circ}C$ at 900RPM compressor speed. For hot gas cycle, the heating capacity was dependent on compressor RPM and it was not much lower than that of the heat pump cycle under high compressor speed. However, the energy consumption of hot gas cycle was much larger than that of heat pump because its COP was lower. The simulation results revealed the heating capacity of hot gas also could be controlled by

compressor discharge pressure and expansion valve throttling area.

The CO_2 mobile air conditioning was tested in two kinds of small compact vehicles by the B-COOL Project [27]. The system performance, fuel consumption and system cost were compared under different ambient conditions. The cool-down curve showed that the CO_2 system could supply adequate cooling capacity to cool the compartment in a certain time. The CO_2 system consumed a slightly higher fuel amount than that of an R134a system at the same thermal load. But for the environmental influence, based on their technologies, the LCCP (life cycle climate performance) calculation results showed that the CO_2 system could reduce the CO_2 emission dramatically even though the fuel consumption of the CO_2 system was a little higher under two different LCCP calculation methods (based on bench data, which is calculated by theoretical vehicle models with typical engine efficiencies, and vehicle road test data, whose fuel consumption is measured as a function of ambient temperatures, respectively) [28]. No direct emission due to CO_2 properties mainly contributes to the total CO_2 emission reduction. The manufacturing cost comparison implied that the total system cost was increased significantly and it was very hard to be reduced to the same level of the R134a system under the current CO_2 technologies.

Despite the technical challenges, the ability of a heat pump to provide high heating capacity and system COP compared with conventional coolant heating or electric resistance heater is essential for the emergence of HEVs and FEVs. But there are more investigations to be expanded to reconsider electrically driven hermetically sealed heat pumps, compact heat exchanges, and control devices. After a thorough review on CO_2 heat pumps and refrigeration cycles, Ma et al. [29] concluded that some modifications such as using internal heat exchanger, two-stage compression, and expansion work recovery as well as enhancing heat transfer could improve the carbon dioxide transcritical cycle performance to be on a level similar to that of a conventional heat pump system. It is implied that it is possible for transcritical CO_2 heat pump systems to become much more popular.

2.3. Advances in other working fluid systems

Besides R134a and CO_2, other potential working fluids used in mobile vapor compression cycles are also studied. Ghodbane [30] analyzed the potential of R152a and some hydrocarbons such as R290, R600a and RC270 as the alternative refrigerants of R134a used in mobile climate control systems. The secondary loop system as shown in Fig. 10 using R152a as the working fluid showed a very good performance in cooling and heating, although COP of R152a secondary loop was 5∼12% lower depending on the ambient and driving conditions. What is more, R152a and other hydrocarbons offer a great benefit in reducing the total equivalent warming impact (TEWI). The shortcomings of the secondary loop are the slower response to load changes, the complex system connections and the increasing cost in components, replacement, and maintenance.

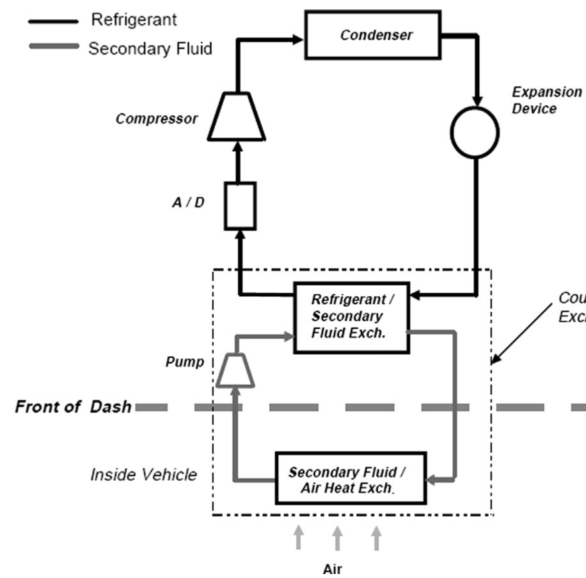

Fig. 10. Secondary loop set-up [30].

2.4. Challenges in vapor compression AC/HP systems

Although vapor compression cycle heat pump systems display higher performance characteristics compared with the original heater core system, there are still some problems or practical issues that should be solved before they could be widely spread in EVs.

2.4.1. Lower COP under cold conditions

The first problem is the relatively lower COP under very cold conditions for R134a HP systems [9,31]. Antonijevic and Heckt's experiments showed that there was a very thick frost layer covered on exterior heat exchanges when the ambient temperature decreased although they believed this could not stop HP operation [13]. Hosoz and Direk's experimental data revealed that heat pump operation could supply adequate heating capacity to the compartment only in mild weather conditions when the working fluid is R134a [32]. And the system performance would decrease dramatically with decreasing outside ambient temperature. They suggested redesigning the exterior and interior heat exchangers and higher temperature heat resource might be the options to improving heating mode performance. So the heat exchangers still need more attention and higher performance heat exchangers are needed in the future under both cooling and heating conditions. Steiner and Rieberer [33] established a reversible CO_2 cycle for exterior heat exchanger defrosting. The experimental results showed that the defrosting of the exterior heat exchanger at the chosen operating condition took less than 2 minutes with reverse cycle defrosting. Their numerical studies revealed that the reverse CO_2 cycle defrosting process for the investigated system occurred at subcritical operating conditions (condensation at constant temperature). Kim et al. [34] tried to improve the CO_2 heat pump system performance through the re-arrangement of heat exchangers in electric cars. The effect of arrangement of the radiator and outdoor heat exchangers on HP system performance was experimentally studied. The improvements of heating capacity and COP were up to 54% and 22%, respectively, when the cold ambient air was heated by the radiator first. However, the improvement only worked under the heating mode. Under the cooling mode, the cooling capacity and COP were decreased by 40∼60% and 43∼65%, respectively, because higher air inlet temperature deteriorated the gas cooler performance.

2.4.2. Special component design and consideration

The second challenge is special components used in the EV's HP systems. The common structure of 4-way valve consists of a moving block inside. The technology is widely used in stationary residential HP units. Considering the severe vehicle operation conditions, the moving block might not function because of long-term vibration and/or external strike. The same problem also will happen to the other check valves and solenoid valves. More long-time experiments are essential for the heat pump system

with the 4-way valve. The safety, durability and reliability should be guaranteed before it can be used in EV's climate control system.

One of the key components in EV's climate control system is electric compressor. There are few open resources published about the electric compressor developments and advances. Performances of electric compressors only have been studied in entire mobile AC/HP systems [35,36]. Because of commercial consideration, these studies do not supply any detailed experimental data and characteristics. Cardol et al. [37] experimentally studied the DC/AC converter and the compressor. Based on the test data, a semi-empirical model was proposed for the prediction of the compressor work, mass flow rate, and discharge temperature. Cuevas et al. [38] did the similar work and also gave some experimental performances of the electric scroll compressor with variable speeds. A cooling capacity prediction model was proposed for the different compressor operating conditions. In a summary, higher efficiency, lower energy consumption and broader operation range are the fundamental requirements for the next generation EV's compressor.

When system is switched to heating mode, exterior and interior heat exchangers are used as evaporator and condenser, respectively. Under this mode, the mass flow distribution and defrosting should be paid more attentions on exterior heat exchanger. And the interior heat exchanger (working as condenser) should sustain a higher burst-pressure when it is designed as an evaporator.

2.4.3. *Concept of integrated thermal system design*

The third challenge is thermal management system design concept in EVs. Battery thermal management system is greatly impacted by cabin climate control system [39]. The mode of climate control system and battery mounting locations also will affect the air-cooled battery inlet temperature. Simulation results demonstrated that engine internal temperature and the cabin heater/air-conditioner power demand could significantly influence the optimal solution for the energy management strategies (EMS), accordingly fuel efficiency and emissions of plug-in hybrid electric vehicles (PHEVs) [40]. Kambly et al. [41] studied the effect of air conditioning and heating system energy consumption on vehicle driving range in PHEVs numerically. Based on the results, they pointed out that the designer should understand that performance and efficiency of climate control system will influence the vehicle's sustainability objectives. From these results, the concept of integrated thermal management system should be established. It will be composed of air conditioning and heating system, motor heating and cooling system, electronic devices cooling system. The design engineer of climate control system should have a broad background and higher-level view on the entire energy usage in electric vehicles. No matter electricity or waste heat, all the energy resource should be utilized in thermal management system.

2.4.4. *Alternative refrigerants*

The fourth challenge is alternative refrigerant for the future environmental consideration. Although R134a is still dominant in mobile AC system, the European Union has passed the regulation to restrict the high GWP refrigerant in cars [42]. Some new refrigerants such as R1234yf are under consideration by the mobile industry and academic society [43–45]. But the HP system performance of R1234yf is very limited in open literatures and reports. Because the thermodynamic and transportant properties of R1234yf are similar or worse compared with R134a [46,47,48,49], more tasks need to be done before it could be widely accept in EVs. About CO_2 as working fluid, it is really an environmental-friendly refrigerant and shows a good performance in lower ambient temperature. The difficulties are cost (component production, replacement, maintenance), high operation pressure, lower COP under high ambient temperature.

3. Non-vapor compression AC/HP system

3.1. *Application of magnetocaloric effect*

The magnetic cooling/heating is based on the magnetocaloric effect (MCE) when it is applied to different metallic materials and new alloys named magnetocaloric materials (MCM) [50,51,52]. When MCM is subjected into a strong magnetic field, the heat will be generated as a consequence of the intrinsic effect of spin orientation. During this phase, the MCM will be magnetized and the generated heat can be used to warm the car compartment. When the MCM is taken out of the magnetic field, it will be a demagnetization phase and the temperature of MCM will decrease because of the intrinsic spin random orientation. So the cooling capacity is produced at this stage. The schematic diagram of a magnetic-refrigeration cycle with two phases is shown in Fig. 11 [53]. Gómez et al. [54] have completed a comprehensive review of MCE application on refrigerators near room temperature in the past decades. The new mobile climate control system will be composed of the above two phases with both cooling and heating. According to the characteristics of MCM, a reversible AC system combined with cooling and heating was proposed for HEV or FEVs' climate control based on magnetic technologies under near room temperature [55,56]. The prototype is shown in Fig. 12 [55]. The prototype showed that the system can supply 7 °C cold source under ambient temperature 30 °C and the system COP is about 3–7 which is comparable or larger than the conventional vapor compression cycle.

Torregrosa-Jaime et al. [57,58,59] described the ICE project in details and published the first-round experimental results in application of MCE heat pump system in fully electric minibus. ICE Project is sponsored by the European Union and European mobile industry to apply Magneto Caloric heat pump systems to fulfill the thermal comfort and energy requirements of FEVs [60]. The climate control system was consisted of magnetocaloric heat pump, load distribution system, microclimate control system. In order to gain continuous thermal capacity, the heat pump should be implemented in a rotary device [61,62]. So far, only

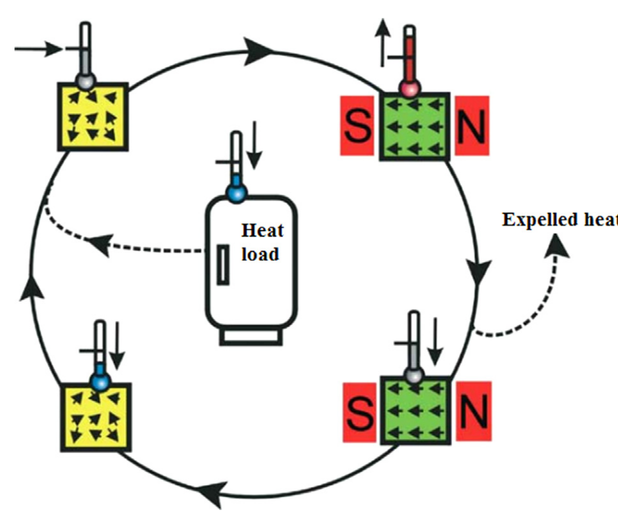

Fig. 11. Schematic representation of a magnetic-refrigeration cycle, which transports heat from the heat load to the ambient. Yellow and green depict material in low and high magnetic field, respectively [53]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

numerical model is set up to calculate the thermal load of heating and cooling under specific conditions. The authors proposed a design tool for analysis and optimization of air conditioning system for an electric minibus [63]. The tool developed in MATLAB-Simulink can be used to predict the transient and steady system performances. The calculation result indicated the thermal load was more than 3400 W with a temperature difference 43 K which was too demanding for the current state-of-art magneto-caloric heat pump features (around 200 W at $\Delta T = 20$ K or 1700 W at $\Delta T = 11$ K) [64,65]. The solution still need be optimized to improve the overall efficiency not only on heat pump system but also on the microclimate control strategy.

The benefits of the MCE heat pump system are as the followings: simpler system, save electricity or SOC, no harmful environmental issues. The challenges for this technology application include MCM selection, more power needed at high temperature difference, system and heat exchanger design, secondary fluids and high enough magnetic fields.

3.2. Application of thermoelectric effect

Thermoelectric cooling chips (TECs) have the advantages of having no moving parts, no noise, long life, no refrigerants, small size and precise temperature control [66]. Compared to conventional vapor compression cycle, their COP is extremely low. Currently, they are only used in seat heating and cooling in some luxury cars. But in a TEC device, heating or cooling can be easily switched by changing the electricity current direction. Alaoui and Salameh [67] thought electric heater, fuel-fired heater and heat pump were not the final solutions in EV's thermal management system. They developed a novel system for thermal management of EV/HEVs. The system was a Peltier-effect heat pump and the design, fabrication and testing of this system were detailed. During the test, the current and the temperature variation inside the battery were recorded in heating and cooling modes. The results proved the feasibility of the technology but the COP was relatively low, which were 0.65 and 0.23 in heating and cooling modes, respectively. In the study of Cosnier et al. [68], a COP higher than 1.5 for cooling and higher than 2.0 for heating could be obtained with a current of 4–5 A and a temperature difference of 5~10 °C using their TEC system setup. Numerically study results by Miranda et al. [69] revealed that TEC cooling system had a transient performance with a COP higher than 1.7 under mild ambient temperature and 0.55 under stringent ambient conditions. Meanwhile, their TEC simulation model also predicted that a COP higher than 1.7 was achieved in the heating mode. But they also pointed out the successful usage of TECs in electric vehicle was strongly dependent on the volume of car size and car body insulation.

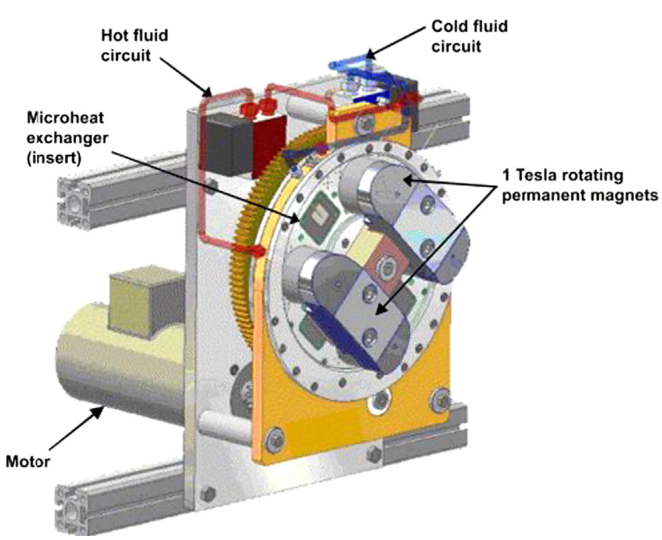

Fig. 12. Magnetocaloric heat pump prototype [55].

Although some thermal-driven AC and refrigeration systems such as adsorption AC system [70,71] have been proposed and reviewed, they still cannot be used in EVs' climate control system because there is no waste heat for system operations.

A brief comparison between the previous main HP technologies is shown in Table 2 including advantages and disadvantages/limitations. It helps design engineers to understand and select a specific and available technology for the real applications.

4. Conclusion

In the present paper, a comprehensive review was performed on the state-of-art of electric vehicle's climate control system. The hybrid electric vehicle and full electric vehicle were included. The cycles, experiments, technologies and challenges in this field have been analyzed. In the EV's climate control system, heat pump (commonly, COP is larger than 1.0) seems a more sustainable solution. It can be realized in R134a, CO_2, magnetocaloric effect, thermoelectric effect and other environmental-friendly working fluids. Each technology has its specific advantages and disadvantages/limitations that have been comprehensively analyzed and pointed out in the present paper.

Considering energy consumption efficiency and vehicle mileage improvement, heat pump is a good option in EV's climate control system. Although there are a number of different HP configurations and experiments, no exciting achievements happened on the essential issues. So, the technology is a little far away from the real practical EV before some difficulties are solved. The difficulties include the high performance interior and exterior heat exchangers, 4-way valve and check valves, lower COP under cold weather, defrosting of exterior heat exchanger, alternative refrigerant and so on. MCE research and MCM technologies developed very fast in the past few years, especially the application under room

Table 2
A brief comparison between available HP system technologies in EVs.

HP system technologies	Advantages	Disadvantages/limitations
Vapor compression	High capacity density; compact system; normally COP > 1.0; current AC technologies can be used.	Lower COP under extreme conditions; control strategy; component re-design; driving range losses; alternative refrigerant issue.
Magnetocaloric effect	Quiet; compact system; easy mode switch; saving the EV's battery; no alternative refrigerant issues.	Less capacity density; MCM material; large magnetic field; new heat exchangers design; poor COP under large temperature difference; driving range losses.
Thermoelectric effect	Quiet; compact system; easy mode switch; no working fluid; no moving parts.	Less capacity density; lower COP; driving range losses.

temperature. The heat pump system of MCE application in EV has a very high transient COP and it is simpler compared with vapor compression HP systems. The challenges for MCE HP systems are MCM selection, system control and heat exchangers. HP systems based on thermoelectric effect have a very low COP and it appears a good supplementary method for future EV's climate control systems.

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